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A Diffraction Grating Autocorrelator for Measurement of Single Ultrashort Light Pulses

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Abstract. A simple autocorrelation scheme for measurement of single ultrashort light pulses in the 1–500 ps range is proposed. Only a diffraction grating and a mirror are utilized to obtain a variable time delay between two collinear beams. The advantages of the proposed method and the effect of the grating dispersion on the autocorrelator performance are discussed.

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The autocorrelation technique is widely used for the measurement of ultrashort light pulses. Although it does not provide complete information concerning the pulse shape, the autocorrelation pulse evaluation avoids the prohibitive cost of the streak-camera measurements.

In recent years special attention was paid to the methods for single-shot autocorrelation which are especially suitable for low-repetition-rate lasers. Since the pioneering work, utilizing two-photon fluorescence [1], a number of techniques for individual-pulse duration measurements were proposed. In most of them the light beam is splitted into two beams, which are made to generate noncollinear second harmonic at a high angle in a nonlinear crystal [2–5]. This method has two advantages: 1) the variable time delay is automatically introduced by the angle between the two interacting beams, and 2) the noncollinear second-harmonic generation (SHG) results in a background-free autocorrelation function.

More recently a diffraction grating was used to produce a linearly increasing time delay with respect to the beam cross-section of the light pulse [6, 7]. Wyatt and Marinero [6] have used a complicated optical arrangement, incorporating a diffraction grating at grazing incidence to record second-order autocorrelation function (ACF) with 1 ps time resolution. In [7] two diffraction gratings in a Michelson-like interferometer provided variable time delay for single-shot pulse measurement. The second-order ACF is obtained by means of a noncollinear SHG with estimated 0.2 ps time resolution. In this paper we propose and analyze a simple autocorrelator in which only a grating and a mirror are used to obtain the necessary for autocorrelation pulse measurement time delay between two parts of a light beam. The advantages of the device and the effect of the grating dispersion on the SHG are discussed.

The Autocorrelator

We utilize the linearly-increasing time delay with respect to the beam cross-section, produced when the beam is diffracted by a grating, as shown in Fig. 1a. One half of the light beam, denoted as A is diffracted directly into m^{th} order by a grating G, while the other half of the beam B is diffracted into the $-m^{\text{th}}$ order after a reflection by a mirror M. The latter is situated normally to the grating. The angle of incidence is chosen in such a way, that the diffracted beams are normal to the grating surface. In this case the grating equation simplifies to:

$$m\lambda = a \cdot \sin\alpha, \tag{1}$$

where m is order of diffraction, λ is the mean wavelength of the light pulse, a is grating constant, and

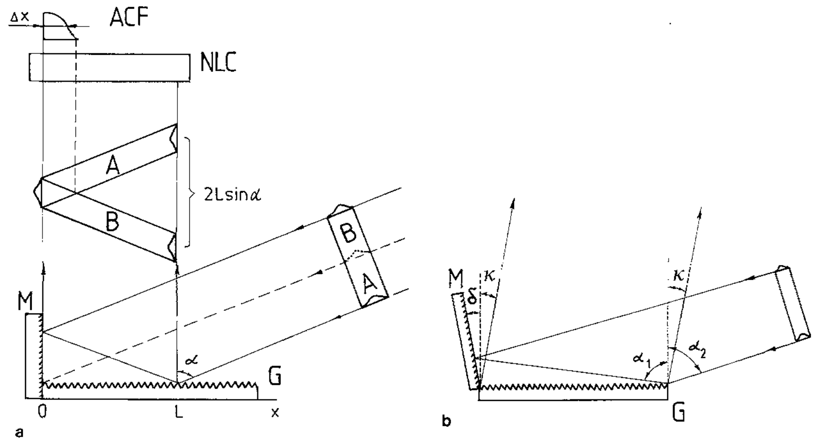

Fig. 1a and b. Schematic diagram of the diffraction-grating autocorrelator (G: diffraction grating, M: totally reflecting mirror, NLC: nonlinear crystal, ACF: autocorrelation function, A, B: ultrashort light pulse). (a) The mirror M is normal to the grating, and (b) the mirror M is inclined at an angle δ with respect to the normal position

α is angle of incidence. The same equation holds for the reflected by the mirror part of the beam, if the mirror is normal to the grating. For the conditions, mentioned above, the time delay between a ray diffracted directly at a point x and a ray, diffracted at the same point after reflection by the mirror, is

$$\tau(x)=\frac{2x\sin\alpha}{c}, \tag{2}$$

where $\tau(x)$ is the time delay, corresponding to the point x and c is speed of light.

In this way two collinear beams are formed, which are diffracted into the m^{th} order normally to the grating and having linearly increasing time delay from zero (at a point $x=0$) to $2L\sin\alpha)/c$, where L is the length of the illuminated part of the grating. It is worth mentioning that the beam should be properly expanded by a cylindrical telescope and a uniform-intensity part of it should be used in the measurement. This expansion may be less, if the grating is used at a grazing incidence.

It is also possible to obtain collinear beams A and B in the case when the angle between the mirror M and the grating G differs from 90° by an angle δ. Then the angles of incidence α_1 and α_2 are determined by (Fig. 1b):

$$2m\lambda=a(\sin\alpha_1+\sin\alpha_2), \tag{3}$$

$$2\delta=\alpha_2-\alpha_1. \tag{4}$$

The diffracted pulses will propagate in the direction, defined by an angle κ, which is derived from

$$2\sin\kappa=\sin\alpha_2-\sin\alpha_1. \tag{5}$$

The main advantage of this arrangement is that the back-reflections to the laser are avoided.

For simplicity, we will continue from now with a normally situated grating and a mirror. Assuming uniform spatial distribution of the beam in the plane of incidence, the corresponding amplitudes of parts A and B of the beam can be written in the form

$$E_A=E_0\cdot F[t-(x/c)\sin\alpha], \tag{6}$$

$$E_B=E_0\cdot F[t+(x/c)\sin\alpha], \tag{7}$$

where $F(t)$ is the temporal pulse profile.

The autocorrelation function may be obtained by means of a second-harmonic generation in a nonlinear crystal. The intensity distribution of the SHG is easily derived [5]

$$I_2(x)=C\cdot G^{(2)}[(2x/c\tau_p)\sin\alpha], \tag{8}$$

where C is a constant, $G^{(2)}$ is a normalized ACF, and τ_p is the duration of the incident pulse. If Δx is the half width of the autocorrelation trace, the pulse duration is determined by

$$\tau_p=(\gamma\cdot\Delta x/c)\sin\alpha, \tag{9}$$

with γ as a pulse-form factor [8].

Because the second-order ACF is a symmetrical one, one can use only half of it to estimate the pulse duration, as is in the case.

If a constant time delay τ_d is inserted into the lower half of the beam, the zero point of the autocorrelation function is displaced to a point $x_d=(n-1)l_d/2\sin\alpha$, where n is the index of refraction of a plane-parallel piece of glass of a length l_d. In this way the total ACF may be recorded.

Slight detuning of the mirror M or detuning of the grating-mirror system as a whole with respect to the angle α introduces a small angle between the two diffracted beams. This leads to noncollinear SHG, which gives a background-free ACF.

Finally, if there is a small angle ε between the two diffracted beams, interference fringes, spaced at a distance λ/ε are readily observed. The interference pattern represents a first-order ACF and may be used for pulse duration measurements as well [9].

Discussion

In this section we shall deal with the performance of the autocorrelator, the influence of the grating dispersion and the choice of the nonlinear crystal.

The main advantage of the proposed autocorrelator is its simplicity, compared to the other grating autocorrelators [6, 7]. Using different gratings with respect to the grating constant and different orders of diffraction, pulse durations in a very wide range can be measured. For subnanosecond pulses incidence angles close to 90° (grazing incidence, $\lambda \lesssim a$) should be used. For these conditions maximum delay of $2L/c$ is obtained. With a 5 cm-long grating it is possible to measure 0.5 ns pulses. When measuring shorter pulses, the length of the autocorrelation trace becomes smaller, which complicates the pulse-width measurement. In this case one should use lower orders of diffraction and gratings with a larger constant a, corresponding to smaller incidence angles α. This results in shorter time delays and longer autocorrelation traces. For very short light pulses (1–10 ps range) coarse gratings (300–600 l/mm) are suitable. For shorter pulses the main limitation will arise from the walk-off effect in the nonlinear crystal [3].

The beam, diffracted by the grating, becomes divergent, due to the finite spectral bandwidth and the angular dispersion. This divergence may influence the process of SHG in the nonlinear crystal and should be taken into account. Assuming a Gaussian-shaped pulse of a time duration τ_p, it is easy to calculate the divergence of the beam in the plane of incidence, which is due to dispersion

$$\Delta\theta_{\mathrm{disp}} = 0.44 \frac{\lambda^2}{c\tau_p a}. \qquad (10)$$

The shorter is the light pulse, the wider is the spectral bandwidth and the higher is the divergence. Because the divergence is proportional to the angular dispersion $d\theta/d\lambda = m/a \cos\alpha$, one should use again for short-pulses measurement first-order diffraction and coarse gratings. Thus, the divergence due to dispersion can be kept low if one employs gratings with constant a inversely proportional to the pulse width, see (10). Combining (9) and (10) one obtains

$$\Delta\theta_{\mathrm{disp}} \cdot \Delta x = 0.31\lambda. \qquad (11)$$

This equation may help the evaluation of the divergence for a fixed wavelength and an autocorrelation trace of a convenient length. For example, if the pulse width is 5 ps at 1.06 μm wavelength and we use a grating which provides an autocorrelation trace of 1 mm, the divergence is only 1 arcmin. This value is acceptable for most of the available nonlinear crystals.

As mentioned above, in order to perform background-free measurements (BFM), it is necessary to produce noncollinear SHG. If the two diffracted beams A and B are propagating in the crystal at an angle σ, the condition $\sigma > \Delta\theta_{\mathrm{pm}}$ is imposed on this angle, where $\Delta\theta_{\mathrm{pm}}$ is the full width of the phase-matching angle for collinear SHG. The full width depends on the crystal type and its length, $\Delta\theta_{\mathrm{pm}} = \lambda/2 \cdot \beta l_c$. The crystal length l_c is chosen to be smaller than: $l_{\Delta\theta} = \lambda/2 \cdot \beta\Delta\theta_{\mathrm{disp}}$ or $l_{\Delta\lambda} = 2\pi/g \cdot \Delta\lambda$, whichever is less. Here β stands for the walk-off angle, $g = \partial k/\partial\lambda$ (k being the wavevector), and $\Delta\lambda$ is the spectral width [10]. Note that this autocorrelator provides BFM at small angles for the nonlinear interaction. This makes possible to use relatively long nonlinear crystals, suitable for collinear SHG. The SHG is more effective in this case and the sensitivity of the method is higher. An important advantage of the proposed autocorrelator is that for the whole range of pulse durations 1–500 ps a crystal of a fixed orientation may be used.

BFM can be performed using oe-e type SHG and a $\lambda/2$ plate, inserted into the lower part A of the incident beam. For very short pulses the thickness of the $\lambda/2$ plate should be taken into account, because the zero point of the ACF will be displaced.

Considering the interference method for measuring ultrashort light pulses [9], any desired fringe separation is easily obtainable, independently on the time delay. This facilitates the interference pattern registration and processing. Replacing the nonlinear crystal with a photodiode array or with a photographic plate and counting the number of the interference fringes, the pulse width can be easily deduced. Measurements in a very wide spectral range can be performed for wavelengths, where no suitable nonlinear crystals are available and the power levels of the measured pulses are extremely low.

Conclusion

We have proposed a simple and versatile method for measuring single ultrashort light pulses, using only a diffraction grating and a mirror. We have shown that for very short light pulses the divergence due to dispersion can be easily lowered, using coarse gratings and providing at the same time autocorrelation traces of appropriate length. A noncollinear SHG in conventional crystals for collinear SHG is readily achieved, resulting in a highly sensitive background-free measurements. If the interference pattern of the two diffracted beams is observed, the electric-field amplitude ACF may be used to estimate the pulse duration in a spectral region, where no suitable nonlinear media exist.

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